Shaping Human Movement via Bimanually-Dependent Haptic Force Feedback

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***Abstract*—Haptic feedback can enhance training and performance of human operators; however, the design of haptic feedback for bimanual coordination in robot-assisted tasks (e.g., control of surgical robots) remains an open problem. In this study, we present four bimanually-dependent haptic force feedback conditions aimed at shaping bimanual movement according to geometric characteristics: the number of targets, direction, and symmetry. Haptic conditions include a virtual spring, damper, combination spring-damper, and dual springs placed between the hands. We evaluate the effects of these haptic conditions on trajectory shape, smoothness, and speed. We hypothesized that for subjects who perform worse with no haptic feedback (1) a spring will improve the shape of parallel trajectories, (2) a damper will improve the shape of point symmetric trajectories, (3) dual springs will improve the shape of trajectories with one target, and (4) a damper will improve smoothness for all trajectories. Hypotheses (1) and (2) were statistically supported at the $p < 0.001$ level, but hypotheses (3) and (4) were not supported. Moreover, bimanually-dependent haptic feedback tended to improve shape accuracy for movements that subjects performed worse on under no haptic condition. Thus, bimanual haptic feedback based on geometric trajectory characteristics shows promise to improve performance in robot-assisted motor tasks.**

***Index Terms*—haptic guidance, bimanual coordination, path and trajectory following, human performance**

I. Introduction

Haptic feedback holds great promise as a tool to improve motor performance and skill training. Haptic feedback, when designed to guide motion or provide performance indicators, appears in research on medical training simulators [1], [2], sports training [3], [4], and rehabilitation exercises [5]–[7], to name a few. In these applications, researchers have tested various forms of haptic feedback including vibration cues [5], [7], [8] and virtual forces [2]–[4], [6]. Vibration cues serve to provide extrasensory information (e.g., situational awareness or direction cues), while virtual forces change the dynamics of a task to assist or resist an operator. Overall, the results of these tests tend to show reduction in movement error or improvement in other specified performance objectives, like smoothness, for well-designed feedback strategies.

The paradigm for designing haptic feedback currently relies on measured performance objectives (e.g., error) as related to predetermined, "desired" trajectories or environmental factors of a given task. Researchers use haptics to both assist and resist operators based on these dependencies [9]. Assistive feedback aids users to improve performance and potentially encourage perseverance in training. In two path following studies, vibration cues informed subjects of significant deviation from the intended path [10], [11]. For both studies, the trials with vibration cues correlated with decreased positional error. For one study, the cues also correlated with improved speed given additional smoothness-based feedback [10]. Haptic assistance has also been implemented via guiding forces. Researchers have employed guidance via proportional-derivative (PD) control to train subjects to follow 3D paths in simple path following tasks as well as surgical training tasks [12]–[14]. This kind of haptic feedback was reported to reduce positional error and improve efficiency as compared to visual guidance alone. Similar haptic guidance has been used in rhythmic tasks to decouple bimanual movements more accurately [15]. In the case of motor skill training, resistive haptic feedback is hypothesized to enhance adaptation and learning over assistive feedback due to a developed reliance on the assistance [9]. Several studies have shown that in both simple reaching tasks and surgical training tasks, subjects who experience resistive or error enhancing feedback learn better than their counterparts who receive assistive feedback or no feedback at all [2], [16]. While all these prior approaches to haptic feedback design show promise for improving motor performance and training, they require exact specification of a desired trajectory and have not fully considered bimanual coordination.

Bimanual coordination is an important facet of performance in many motor skills, both elementary and advanced. Prior work has shown that bimanual movements can be classified according to geometric characteristics, like direction and symmetry, through robotic sensing [17]. This type of classification is of interest in interdisciplinary, motor control studies [18] and correlates with varied performance during path following [19], [20]. By designing haptic feedback with regard to a high-level, geometric classification of bimanual coordination, it becomes independent of unique trajectories. Also, we can potentially shape movement of the bimanual limbs by coupling them through augmented haptic forces. To investigate the effects of bimanually-dependent haptic feedback on performance as

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related to a geometric classification of bimanual coordination, we conducted a 2D trajectory following experiment and present the results in this paper.

II. Methods

A. Subjects

A total of 11 able-bodied subjects, aged 19 to 31 years (mean 24 yrs), were recruited for the study. Of these subjects, 7 were born as male and 4 were born as female. All subjects provided informed consent in accordance with the UT Austin IRB #00000278. All subjects were right handed except for two. Of the two, one was ambidextrous. This subject reported use of the right hand for writing and throwing and use of the left for activities like swinging clubs or bats. We surveyed subjects on experience with human-machine interfaces using a scale of 1 (no experience) to 4 (able to program a human-machine system). The survey results were evenly distributed for all choices (1s: n=3, 2s: n=2, 3s: n=2, and 4s: n=4).

B. Bimanually-Dependent Haptic Forces

The focus of this work is the assessment of bimanually-dependent haptic forces on performance outcomes of movements with specified coordination. Each haptic force was implemented virtually. All subjects experienced a base haptic force during every movement and one of five bimanually-dependent haptic feedback conditions (Fig. 1). The base haptic force was a vertical 2-dimensional plane constraint that was imposed by stiff, virtual spring forces set with spring constant of $k_p = 120\,\mathrm{N/m}$. This constraint was imposed to ensure the task was 2D and reduce any error due to movement in or out of the plane. The five bimanually-dependent haptic feedback conditions were:

1) **Null:** No haptic forces except for the plane constraint
2) **Spring**: A virtual spring between the hands set at an initial length equal to the distance between starting positions and set with spring constant, $k_s = 10\,\mathrm{N/m}$
3) **Damper**: A virtual damper between the hands and set with damping constant, $k_d = 10\,\mathrm{N/m/s}$
4) **Combo. Spring-Damper**: Additively combined spring and damping forces
5) **Dual Spring**: Two springs grounded at the midpoint of the hands and set with spring constant, $k_{s2} = 15\,\mathrm{N/m}$.

We chose haptic force constants to be perceptible but not impede subjects from completing the task.

C. Trajectory Following Experiment

Subjects sat at a desk with arm rest, computer monitor, and two Geomagic Touch™ haptic devices to perform bimanual trajectory following. We adjusted the setup for subjects to reach the entire workspace comfortably (Fig. 2). Subjects used the haptic devices to control gray, spherical cursors on screen. Trajectories were demonstrated by red spheres of the same size as the cursors. Black traces of the trajectories lasted until the red spheres completed the demonstration. Subjects could replay the trajectory as many times as needed before attempting to reproduce it. However, subjects were instructed not to attempt the trajectory until the red spheres finished the demonstration. Trajectories were demonstrated in this way to mimic demonstration of more complex tasks by an expert to a novice. All trajectories started from the same location and were randomly generated to have a coordination mode, similar to a previous experiment [20]. Coordination modes are sets of trajectories with particular types of symmetry, direction, and number of targets [17], [20]. Number of targets are 1 and 2. Direction types are together (Tog) when the distance between hands decreases, parallel (Par) when the distance between hands remains near constant, and away (Awy) when the distance between hands increases. Symmetry types are mirror (Mir), point (Pt), visual (Vis), and incongruent (Inc). Figure 2 (a), (b), and (c) each show an example of a different

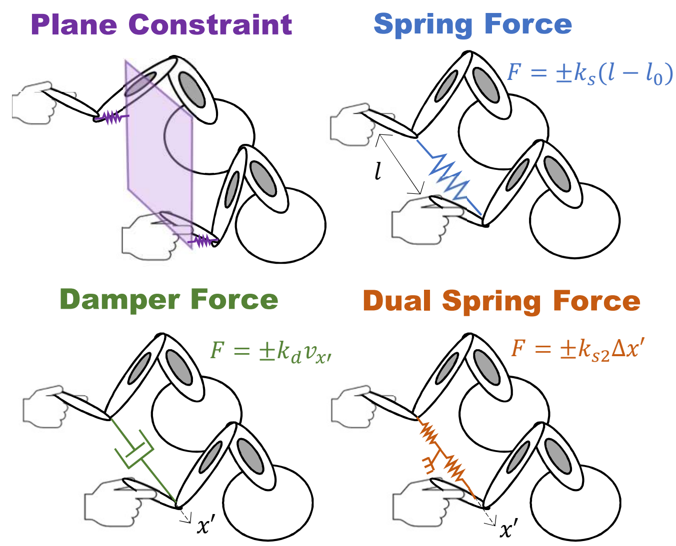

Fig. 1. Illustration of the bimanually-dependent haptic forces used in this study. Springs constrained subjects to a vertical 2D plane for all trials. A virtual spring constrained the distance between hands. A virtual damper constrained velocity toward or away from each hand. A dual spring force pulled the hands together to a central position.

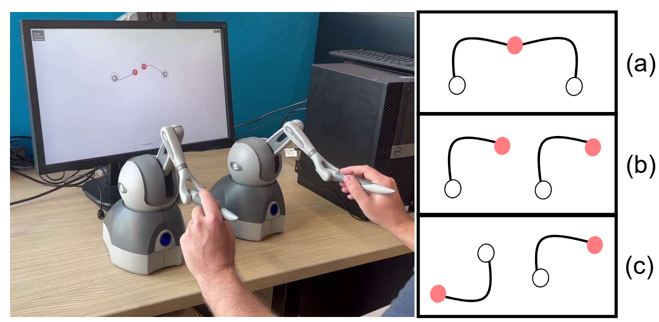

Fig. 2. Bimanual trajectory following with haptic devices and example coordination modes. Trajectories were randomly generated to have a particular coordination mode, defined as having a specified number of targets, direction, and symmetry. For example, (a) has one target, direction of together, and mirror symmetry, (b) has two targets, direction of parallel, and visual symmetry, and (c) has two targets, direction of away, and point symmetry.

coordination mode. Only 11 combinations of targets, direction, and symmetry (i.e., coordination modes) are possible.

The experiment consisted of 1 training session and 4 randomized experimental blocks. For the training session, the primary author demonstrated the task to subjects. Then, subjects performed 16 practice trajectories. Subjects experienced each type of haptic condition during practice but were not explicitly told the types of haptic forces. Subjects were instructed to reproduce each trajectory as accurately and smoothly as possible in one discrete movement. Each experimental block contained one randomized type of bimanually-dependent haptic feedback, including the null condition, and 4trajectories for a particular coordination mode. Therefore 44 trajectories per block were performed (176 trajectories total). All 44 trajectories in each block were randomized both by generation and order.

D. Data Acquisition and Processing

Data were acquired at 120 Hz from the haptic devices and processed with moving average filters. The position data filter was of length 250 ms. The velocity data, acceleration data, and jerk data filters were of length 83 ms. Subject trajectories were trimmed using a log-likelihood ratio onset detection method [21]. For the completion condition, velocity data was continuously monitored until the computed innovations dropped below the onset threshold. Then, the subsequent local minimum was marked as the completion point. Every trajectory was manually checked for errors. Errors include short movement time (<0.25 s), an onset or offset at greater than 20% into the velocity curve, or a sequential movement indicated by clear separation of left and right hand velocity curves. If a subject's trajectory was deemed to have any of these errors, then the trajectory was removed from analysis. A total of 144 trajectories (7.4% of total data) were removed.

E. Performance Objectives

To assess performance, we computed two main performance outcome metrics and one supplementary metric. The first main metric is trajectory correlation error, defined by

$$\text{Trajectory Correlation Error} = 1 - \frac{Cov(\Phi, \Phi^*)}{\sigma(\Phi)\sigma(\Phi^*)} \tag{1}$$

where Φ and Φ^* are matrices of equal length vectors that are tangent to the subject and ideal trajectory, $Cov(\cdot)$ is the covariance function, and $\sigma(\cdot)$ is the standard deviation. Trajectory correlation error is a reflection of shape accuracy as compared to the demonstrated trajectory [20], [22]. The second metric is dimensionless integrated absolute jerk (DIAJ) [20], [23], a measure of smoothness, defined by

$$\text{DIAJ} = \frac{D}{v_{\text{mean}}} \int_D \left\| \frac{d^3\mathbf{x}(t)}{dt^3} \right\| dt \tag{2}$$

where $d^3\mathbf{x}(t)/dt^3$ is the third derivative of position with respect to time, D is the movement time duration, and v_{mean} is the mean velocity.

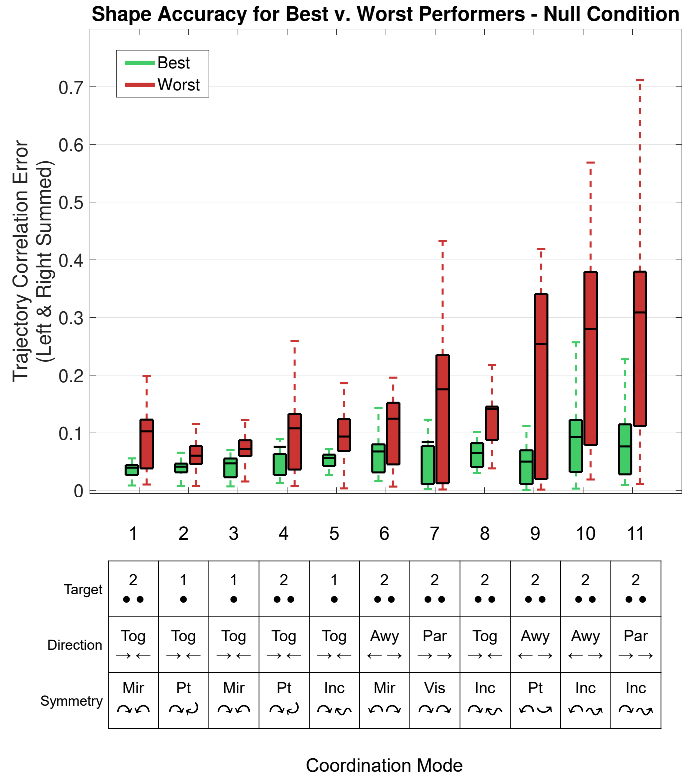

Fig. 3. Shape accuracy box plots for best and worst performers over the eleven bimanual coordination modes during the null condition. Boxes show 25^{th} to 75^{th} percentiles and median. Whiskers extend to minimum points and maximum points within $1.5\times$ the inter-quartile range. The worst performers had higher trajectory correlation error and may benefit more from bimanually-dependent haptic feedback.

For each main performance outcome metric, we summed both left and right hand scores. The supplementary metric was average speed, so we could assess the speed-accuracy trade-off. Speed was averaged for each trajectory and between left and right hands.

F. Statistical Analysis and Hypothesis Testing

For subjects who perform worse under null conditions, we hypothesize: (1) a spring will improve the shape of parallel trajectories due to the distance constraint between the hands, (2) a damper will improve the shape of point symmetric trajectories due to a rotational constraint, (3) dual springs will improve trajectories of one target due to a pull toward a center location, and (4) a damper will improve smoothness for all trajectories due to its velocity resistance and relation to jerk.

To test our hypotheses and analyze effects of bimanually-dependent haptic forces on bimanual coordination modes, we first split subjects into best and worst performers (5:6) for each coordination mode under the null condition by using a normalized score (Fig. 3). This was done because performance augmentation is typically applied to novices or persons who perform worse at a given task. The score was computed as the sum of the assessed performance outcome's median and variance and normalized by the group maximum. Also, coordination modes are ordered by this score.

We fit a generalized linear mixed-model (GLMM) to data from the worst performers with subjects as a random effect and ran several multiple comparison tests [24], [25]. The GLMM was estimated via the Laplace method, and trajectory correlation error was fit with gamma errors and a reciprocal link function, while DIAJ and speed were fit with normal errors. Bimanually-dependent haptic forces were modeled as fixed effects. Effects of experimental block were removed from the model due to clear insignificance. Multiple comparisons were performed using sequential F-tests with Bonferroni corrections.

III. Results

***Hypothesis 1*)** For coordination modes with direction of parallel under the spring condition and spring-damper condition (Fig. 4(a) - Coordination Modes 7 and 11), trajectory correlation error was reduced as compared to the null condition ($F = 7.57, p < 0.001$). The spring condition effect on coordination mode 7 of -0.12 ($F = 9.27, p = 0.010$) and coordination mode 11 of -0.16 ($F = 5.12, p = 0.095$). The spring-damper condition effect on coordination mode 7 of -0.12 ($F = 10.78, p = 0.095$) and coordination mode 11 of -0.21 ($F = 7.36, p = 0.027$).

Regarding speed, the spring condition non-significantly increased average speed of 0.4 cm/s for both coordination modes 7 and 11, ($F = 1.71, p = 0.766$) and ($F = 1.61, p = 0.819$) respectively. The spring-damper condition had increased average speed of 0.9 cm/s ($F = 9.03, p = 0.011$) and non-significantly increased average speed 0.2 cm/s ($F = 0.33, p = 1.000$) for coordination modes 7 and 11.

***Hypothesis 2*)** For coordination modes with point symmetry under the damper condition and spring-damper condition (Fig. 4(a) - Coordination Modes 2, 4, and 9), trajectory correlation error had significant effects ($F = 5.04, p < 0.001$). The damper condition had no effect on coordination mode 2 ($F = 0.81, p = 1.000$), no effect on coordination mode 4 of -0.03 ($F = 1.59, p = 0.833$), and significant effect on coordination mode 9 of -0.18 ($F = 11.22, p = 0.003$). The spring-damper condition had little effect on coordination mode 2 of 0.03 ($F = 2.18, p = 0.560$), no effect on coordination mode 4 of 0.03 ($F = 0.88, p = 1.000$), and significant effect on coordination mode 9 of -0.21 ($F = 13.77, p < 0.001$).

Regarding speed, the damper condition had non-significantly decreased average speed of -0.5 cm/s ($F = 2.25, p = 0.536$), -0.5 cm/s ($F = 2.84, p = 0.369$), and -0.7 cm/s ($F = 4.79, p = 0.116$) for coordination modes 2, 4, and 9, respectively. The spring-damper condition had decreased average speed of -0.7 cm/s ($F = 5.63, p = 0.072$), -0.5 cm/s ($F = 3.06, p = 0.323$), and -1.0 cm/s ($F = 9.05, p = 0.011$) for coordination modes 2, 4, and 9, respectively.

***Hypothesis 3*)** For coordination modes with one target under the dual spring condition (Fig. 4(a) - Coordination Modes 2, 3, and 5), trajectory correlation error had non-significant effect ($F = 0.66, p = 1.000$).

Regarding speed, the dual spring condition had non-significantly increased average speed of $0.5\,\mathrm{cm/s}$ ($F = 2.24, p = 0.540$), 1.2 cm/s ($F = 12.51, p = 0.002$), and $0.5\,\mathrm{cm/s}$ ($F = 3.26, p = 0.286$) for coordination modes 2, 3, and 5, respectively.

***Hypothesis 4*)** For smoothness (Fig. 4(b)), the damper condition showed a reduction in DIAJ for all coordination modes but to no significant effect ($F = 1, p = 1.000$). Table II reports the effects of all haptic conditions on DIAJ.

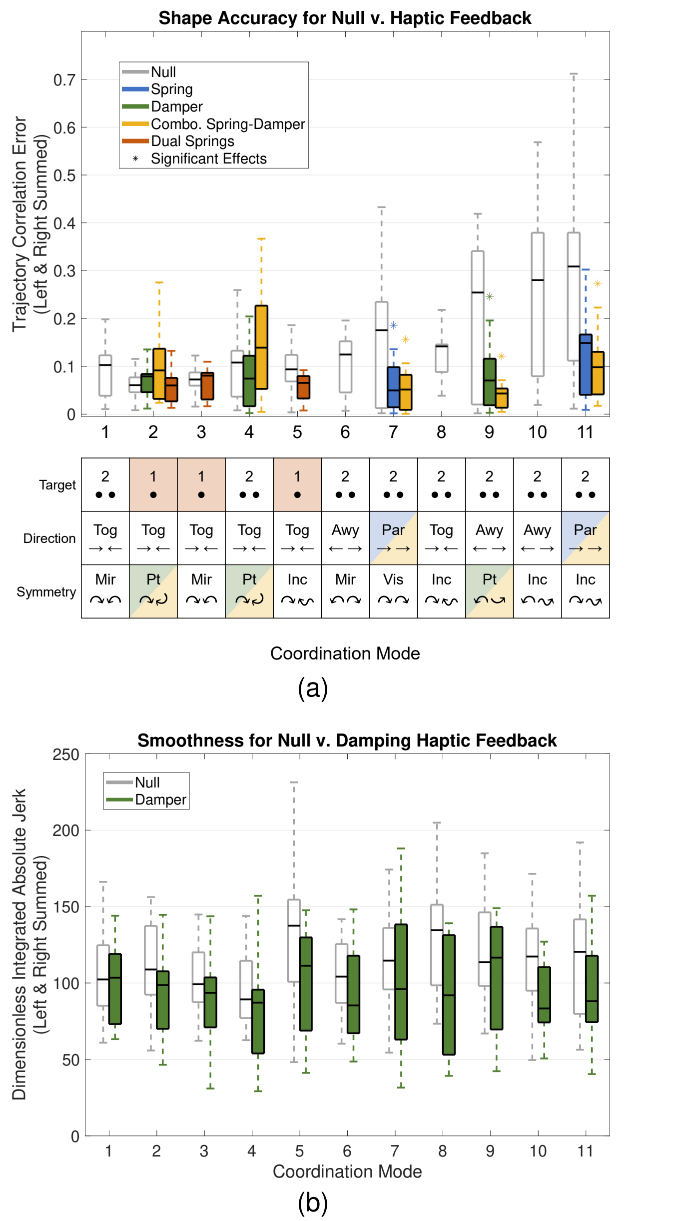

Fig. 4. (a) Shape accuracy and (b) smoothness box plots for haptic conditions as related to hypotheses for worst performers. Boxes show 25^{th} to 75^{th} percentiles with mean. For (a) shape accuracy, whiskers extend to minimum points and maximum points within 1.5× the interquartile range. For (b) smoothness, whiskers extend in both directions to points within 1.5× the interquartile range. Stars above boxes indicate a statistically significant effect of bimanually-dependent haptic feedback as compared to the null condition. Colors in the coordination mode table reflect hypotheses pairings of a coordination mode and haptic feedback condition.

TABLE I
SHAPE ACCURACY EFFECTS OF BIMANUALLY-DEPENDENT HAPTIC FEEDBACK ON WORST PERFORMERS

		Coordination Mode										
		1	2	3	4	5	6	7	8	9	10	11
	Num. Targets	2	1	1	2	1	2	2	2	2	2	2
	Direction	Tog	Tog	Tog	Tog	Tog	Awy	Par	Tog	Awy	Awy	Par
	Symmetry	Mir	Pt	Mir	Pt	Inc	Mir	Vis	Inc	Pt	Inc	Inc
	Haptic Force											
Traj. Corr. Err	Spring	-0.05	0.01	-0.01	0.00	-0.04	0.02	-0.12**	-0.01	-0.03	-0.17	-0.16
Traj. Corr. Err	Damper	-0.03	0.02	-0.02	-0.03	-0.01	-0.02	-0.10	0.02	-0.18**	-0.01	-0.16
Traj. Corr. Err	Combination	-0.02	0.03	0.01	0.03	0.01	-0.05	-0.12**	-0.03	-0.21***	-0.16	-0.21*
Traj. Corr. Err	Dual Spring	0.03	0.00	0.01	0.01	-0.03	0.02	0.01	0.12	-0.13	-0.08	-0.07
Speed (cm/s)	Spring	-0.8	-0.9*	-0.9*	-0.7	-0.2	-0.3	0.4	-0.4	-0.5	-0.5	0.4
Speed (cm/s)	Damper	-1.2**	-0.5	-0.2	-0.5	-0.9*	-0.8*	-0.1	-0.2	-0.7	-0.5	0.5
Speed (cm/s)	Combination	-0.7	-0.7	-1.1*	-0.5	-0.2	-0.9*	0.9*	0.0	-1.0*	-0.4	0.2
Speed (cm/s)	Dual Spring	0.3	0.5	1.2**	0.1	0.5	-0.3	1.5***	1.6***	0.2	0.3	1.2**

Entries are estimated effects of bimanually-dependent haptic feedback conditions on coordination modes as compared to the null condition. Green entries indicate a reduction in error. Red indicate an increase in error. Shading is by magnitude of effect. Effects with p-values less than 0.05 are indicated with *, less than 0.01 with **, and less than 0.001 with ***.

IV. DISCUSSION

In this study, able-bodied subjects performed simultaneous, 2D bimanual trajectory following, which required movements of differing number of targets, direction, and symmetry under several bimanually-dependent haptic feedback conditions. We tested if these haptic conditions had effects for worse performers on two main performance outcome measures of accuracy and smoothness, as well as one supplementary performance measure of speed to assess the speed-accuracy trade-off.

With regard to hypothesis (1), we predicted a virtual spring placed between the hands would improve the shape of bimanual trajectories with parallel direction. This is because parallel bimanual trajectories are characterized by a constant inter-manual distance [17], and the spring resists movements without a constant inter-manual distance. According to our results, the spring and combination spring-damper conditions improved shape accuracy as measured by trajectory correlation error for both coordination modes with direction of parallel. Three of the four experimental conditions were to significant effect ($p < 0.001$). Thus, we accept hypothesis (1). There was not a decrease in speed for these haptic conditions as compared to the null condition, which indicates the increase in accuracy is likely not due to an intentional reduction in speed.

With regard to hypothesis (2), we predicted a virtual damper placed between the hands would improve the shape of trajectories with point symmetry because it resists non-rotational movement without maintaining an initial inter-manual distance. According to our results, the damper and spring-damper conditions improved shape accuracy for the highest ranked coordination mode with point symmetry ($p < 0.001$). For other coordination modes with point symmetry, no haptic condition with a damper had any effect. There was a decrease in speed for coordination mode 9 given the damper and spring-damper conditions, but only the spring-damper condition was to significant effect. Therefore, there is a chance that the increase in accuracy was due to a reduction in speed. However, a damper directly acts to resist velocity. Table I shows a reduction in speed given the damper condition for all coordination modes except 11. Therefore, this outcome may instead reflect the changed dynamics of the system rather than an intentional reduction in speed. Thus, we also accept hypothesis (2) with stipulations.

With regard to hypothesis (3), we predicted a dual-spring grounded at the mid-point between the hands would improve the shape of trajectories with one target. However, the dual-spring condition had no effect on subjects' shape accuracy for trajectories with one target. Thus, we reject hypothesis (3). There was an increase in speed for these experimental conditions, and one of the conditions was to significant effect. However, due to reasons described previously, this outcome may simply reflect changes in system dynamics rather than intent. We also note that the coordination modes with one target were ranked lower. This means that for the group overall, these coordination modes had lower trajectory correlation error (Fig. 3) and may have been easier to perform. In other words, there may be no need to provide assistance for these types of movements because they are already performed well. There is a chance that given more difficult movements with a single target, this type of feedback may improve performance. However, this requires further study to prove.

With regard to hypothesis (4), we predicted the damper condition would improve smoothness due to its direct impedance to velocity and closer relation to jerk. While the damper condition improved smoothness for all coordination modes, it did not do so to significant effect. Additionally, the combination spring-damper condition tended to worsen smoothness (Table II). Thus, we also reject hypothesis (4).

Generally, bimanually-dependent haptic forces appear to

TABLE II
SMOOTHNESS EFFECTS OF BIMANUALLY-DEPENDENT HAPTIC FEEDBACK FOR WORST PERFORMERS

	Coordination Mode										
	1	2	3	4	5	6	7	8	9	10	11
Num. Targets	2	1	1	2	1	2	2	2	2	2	2
Direction	Tog	Tog	Tog	Tog	Tog	Awy	Par	Tog	Awy	Awy	Par
Symmetry	Mir	Pt	Mir	Pt	Inc	Mir	Vis	Inc	Pt	Inc	Inc
DIAJ: Spring	8	-2	19	20	-1	-11	-17	1	13	40	5
DIAJ: Damper	-12	-25	-4	-14	-14	-8	-12	-32	-10	-20	-13
DIAJ: Combination	18	3	54**	23	33	9	-12	5	25	38	-14
DIAJ: Dual Spring	-5	-21	-10	-11	-34	14	-12	-29	68***	8	-4

Entries are estimated effects of a type of bimanually-dependent haptic feedback on a particular coordination mode as compared to the null condition. Green entries indicate a reduction in DIAJ (i.e., smoother movement), while red indicate an increase in DIAJ. Shading is by magnitude of effect. Effects with p-values less than 0.05 are indicated with *, less than 0.01 with **, and less than 0.001 with ***.

improve shape accuracy of coordination modes 7-11 to greater effect. Interestingly, statistical significance in these effects appears to stem from the geometric properties of both the haptic condition and the trajectories. Contrarily, haptic conditions appear to have little effect on coordination modes 1-6. We also note that this study is non-exhaustive. Its purpose was to investigate the performance effects of several bimanually-dependent haptic feedback conditions on classifications of bimanual coordination. While each haptic condition was designed for a particular class of bimanual coordination, we invite researchers and haptic control designers to use our results as listed in Tables I and II as a guide. Future work derived from these results may be done to more thoroughly investigate our hypotheses or improve upon the design of the haptic feedback conditions for particular studies and applications.

Our approach uses bimanually-dependent haptic forces in a haptically-enabled robotic system given a set of trajectories that can be classified by geometric properties. Applications that fit this approach include bimanual motor tasks, like robotic surgery or rehabilitation. Assistance may be given in a robotic system via bimanually-dependent haptic forces for corresponding trajectories to potentially improve task performance or assist in training. For certain trainees, this type of feedback may reduce error to allow for learning to occur [26]. However, care must be taken so a dependence on the haptic feedback is not formed [9]. While this study only looked at haptic assistance, another consideration is to design similar bimanually-dependent haptic feedback to resist movement or amplify error to improve training [2], [9], [16]. In either case, application-specific considerations should be taken when implementing bimanually-dependent haptic feedback.

This study comes with some limitations. One limitation regards the effect size of bimanually-dependent haptic feedback on performance outcomes. We do not report effect sizes because importance of effect size will depend on the application. Performance outcomes of tasks requiring extremely precise movements, like surgical operations, may be more sensitive to error. In contrast, the outcome of a large, stabilizing movement may not need to be as precise. Also, effect sizes are reported for a small sample size of subjects and only worst performers. Effects may differ for different populations. In particular, better performers may show no improvement or worse improvement for the reported method. Another limitation regards the speed-accuracy tradeoff. We analyzed speed to provide some insight but did not control for speed directly. We made this choice to observe the reaction of subjects to imposed haptic feedback conditions in a motor task performed at a pace of their choosing. This decision was made to provide insight for future applications, such as early phases of motor task training. In future experiments, controlling for speed will help to confirm or contradict the results presented here.

Finally, the bimanually-dependent haptic forces have the potential to impact the positional accuracy of a movement as well as the shape accuracy and smoothness. Prior approaches use position-based feedback to reduce or enhance positional error whereas our forces depend on the positional relation of the hands. Future work will be needed to compare bimanually-dependent haptic feedback to other position-based approaches with regard to both effectiveness and ease of implementation.

V. CONCLUSION

In this work we explored the effects of several bimanually-dependent haptic feedback conditions on classes of bimanually coordinated movements. Haptic conditions consisted of virtual springs and dampers implemented between the hands, which were independent of environmental factors and trajectory positions. This benefit has the potential to impact real-time assistance for a variety of robotic systems, including surgical robots and bimanual rehabilitation robots. We showed that subjects who perform worse under null haptic conditions can improve the desired shape of their movements with particular bimanual haptic feedback but may not be able to improve smoothness. We also discussed that the improvement in shape is unlikely due to an intentional reduction in speed. Future work will further investigate these results, provide application of our approach to real-world bimanual tasks, and develop intelligent ways of implementing bimanually-dependent haptic feedback. Moreover, there is an opportunity to develop a future framework for bimanual haptic assistance in diverse, robot-assisted tasks.

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